(12) EUROPEAN PATENT APPLICATION

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(54) Method for determining a pair of corresponding points between images.

(57) A transport network is constructed of transport paths which transport quantities of light possessed by respective pixels (102, 104) from one of two images (101, 103) to the other, and a pair of corresponding points between the two images is found on the basis of the magnitude of light transport between the pixels minimizing the cost of transportation or a distribution of such magnitudes.

A transport network model is constructed so that flows at inflow points corresponding to various points on one image and at outflow points corresponding to various points on the other image may become magnitudes of a feature quantity of the respectively corresponding points on the images, and a pair of corresponding points composed of the inflow point and the outflow point is determined on the basis of a distribution of the flows within the network model.

FIG. 10

Title of the Invention

Method for determining a pair of corresponding points
between images

Background of the Invention

Field of the Invention

5   The present invention relates, in an apparatus
for recognizing environment by the use of visual information,
to a method for determining a pair of corresponding
points between images which is well suited for recognizing
a three-dimensional space on the basis of stereopsis

10   or successive images.

Also the present invention relates, in an apparatus
for measuring a position, a position measuring apparatus
which is well suited for measuring the position or distance
of an object by the use of a pair of image information

15   derived at different positions or times from the identical
object. The apparatus of this type is indispensable
to various installations which control equipment with
image information (for example, a robot having the sense
of vision, an automatic controller for a vehicle adapted

20   to respond to an exterior scene, and a process controller
interlocked with industrial television).

Description of the Prior Art

As a prior-art method for recognizing environment
on the basis of stereopsis, there has been one wherein

edges are detected from images obtained with both the

eyes (hereinbelow, termed "a pair of stereo images"),

and the corresponding edges are decided in consideration

of the polarities of the edges, to recognize a solid

5   body (Takeshi Hirose, "Technique for Recognizing Solid

Obstacle on the basis of Stereopsis", in the 'Transactions

of the Society of Instrument and Control Engineering',

Vol. 19, No. 8, pp. 50 - 56). This technique has had

such disadvantages that the adjustment of a slice level

10   for edge extraction is difficult and that misrecognition

is sometimes involved in an image where edges are periodically

distributed.

In addition, as prior-art methods for recognizing

environment on the basis of successive images, there

15   have been, e. g., a method based on optical flow (B.

K. P. Horn and B. G. Schunk: Determining Optical Flow,

Artificial Intelligence 17 (1981) 185 - 203) and a matching

method (L. Dreschler and H. H. Nagel: On the Frame-to-

Frame Correspondence between Grayvalue Characteristics

20   in the Images of Moving Objects, German Workshop on

Artificial Intelligence, 81, 18/21, 1981, Springer-Verlag).

The former has had numerous restrictions such as the

fact that it can be used for only an object whose surface

brightness changes smoothly, and the range of application

25   thereof has been limited.

The latter has involved such a disadvantage that the selection of feature points in a number sufficient for expressing an object is difficult.

Further, in the position measuring apparatus of the type specified before, which point of the other image a certain point of one image corresponds to needs to be determined by automatic processing. One of prior-art methods therefor is described in "Science", Vol. 194, 15 October 1976, pp. 283 - 287 (D. Marr and T. Poggio, "Cooperative Computation of Stereo Disparity").

This method is capable of parallel computation, and is therefore suitable for high speed processing. Since, however, it finds the corresponding relation between pixels as to the images each consisting of pixels quantized to two levels, the correspondence is rough. In other words, a certain pixel of one image cannot be caused to correspond to the intermediate position of the pixels of the other image. As a result, the accuracy of a calculated position is unsatisfactory.

Summary of the Invention

A first object of the present invention is to provide a method for recognizing environment which can readily detect corresponding points in a pair of stereo images or successive images and which causes misrecognition little.

A second object of the present invention is to provide a method which precisely detects the corresponding points between a pair of images thereby to improve the accuracy of positional measurement.

To the accomplishment of the first object, the present invention has its first characterizing feature in constructing a transport network which is composed of transport paths for transporting the quantities of light of respective pixels from one of two images to the other, and finding the corresponding images from that transport volume between pixels or that distribution of transport volumes at which the cost of transportation is minimized.

For example, in case of detecting edges from a pair of stereo images to decide the corresponding edges, misrecognition sometimes occurred. The reason is that only the polarities of the edges are considered without taking the intensities thereof (the varying rates of brightness) into account.

As the characteristic of a pair of stereo images, the difference of the images observed from both the eyes is slight, and the image of a certain object is observed as almost equal brightnesses in the images of both the eyes. Accordingly, the corresponding points are determined by finding regions of the same brightness

from the images of both the eyes or by finding points
of equal changes in brightness, whereby the misrecognition
can be lessened.

In a first embodiment, corresponding pixels are
found on the basis of the transport volume between pixels
at which the cost of transportation is minimized in
a transport network for transporting the quantities
of light of respective pixels between two images obtained
with both the eyes.

Besides, as regards successive images, in case
of detecting corresponding points between the two successive
images, if the sampling interval of the images is sufficiently
short, the rate of change in the position or brightness
of an object is slight between the images. Accordingly,
a region having a certain brightness or a position changing
in brightness within one image exists near the same
position within the other image. When this property
is utilized, the detection of the corresponding points
between the two images can be converted into finding
the optimum route in the case of constructing a transport
network which is furnished with transport paths from
the respective pixels of one image to pixels near the
same positions of the other image, and then conveying the
brightnesses or the rates of change in brightness from
one image to the other image through the network.

In a second embodiment, the corresponding pixels
are found on the basis of the distribution of the transport
volumes between pixels at which the cost of transportation
is minimized in the aforementioned transport network.

5   To the accomplishment of the second object, the
present invention has its second characterizing feature
in using a transport network model which has inflow
points corresponding to the respective points of one image
and outflow   points corresponding to the respective

10   points of the other image and in which the flows of
the respective inflow points and outflow points are
set in conformity with the magnitudes of a feature quantity
(such as the brightness or the rate of change in brightness)
of the corresponding points on the images, and determining

15   a pair of corresponding points consisting of the inflow
point and the outflow point from the distribution of
flows within the network.

The transport network model is realized as an electric
circuit by way of example, and it is possible to cause

20   the flows to correspond to current values and the transport
paths between the various points to correspond to resistances.
It is assumed that fixed current sources of values equivalent
to the magnitudes of the feature quantity of the corresponding
points on the images exist at the respective inflow

25   points and outflow points, and steady solutions are

obtained by adjusting the values of the resistances.
On this occasion, the value of a current flowing from
the inflow point to the outflow point denotes the degree
of correspondence between those points on the images

5   which correspond to the inflow and outflow points.

Since the deviation of corresponding points between
two images to be processed is usually slight, the extent
of outflow points to be connected to each inflow point
(namely, the number of transport paths) is not very

1o   large. Accordingly, automatic processing which employs
the transport network model as stated above becomes
practical.

Brief Description of the Drawings

Fig. 1 is a camera arrangement diagram for stereopsis;

15   Fig. 2 is a diagram showing a method of constructing
small regions within images;

Fig. 3(a) is a diagram showing the mean brightnesses
of the respective small regions of right eye's image,
while Fig. 3(b) is a diagram showing the mean brightnesses

2o   of the respective small regions of left eye's image;

Fig. 4 is a diagram showing the arrangement of
a network;

Fig. 5 is a diagram showing the calculated results
of corresponding points;

25   Fig. 6(a) is a diagram showing the mean

brightnesses of the respective small regions of right

eye's image, while Fig. 6(b) is a diagram showing the mean

brightnesses of the respective small regions of left eye's
image;

Fig. 7 is a diagram showing the calculated results

5   of corresponding points;

Figs. 8(a) and 8(b) are diagrams showing the mean

brightnesses of every 4 x 4 pixels derived from successive

images;

Figs. 9(a) and 9(b) are diagrams showing results

10   obtained by subjecting the mean brightnesses of Figs. 8(a)

and 8(b) to second-order differentiation respectively;

Fig. 10 is a diagram for explaining transport paths

which are set for the successive images;

Figs. 11(a) and 11(b) are diagrams showing results

15   obtained by detecting corresponding points;

Fig. 12 is a block diagram of the whole system

of a corresponding point-determining apparatus according

to the present invention;

Fig. 13 is a block diagram of the whole system

20   of a three-dimensional distance measuring apparatus

according to the present invention;

Fig. 14 is a model diagram of corresponding points

in the case of stereopsis;

Fig. 15 is a sketch of images for explaining pre-

25   processing in the case of stereopsis;

Fig. 16(a) is a connection diagram of a transport network model for determining corresponding points on corresponding scanning lines, while Fig. 16(b) is a graph of weighting coefficients which are used for updating resistance values;

Fig. 17 is a model diagram showing the relationships between the positions of corresponding points on images and the positions of measured points;

Figs. 18(a) and 18(b) to Figs. 20(a) and 20(b) are graphs each showing an example of processed results according to the present invention; and

Fig. 21 is a connection diagram of a transport network model in the case of determining corresponding points in a range of two dimensions.

Detailed Description of the Preferred Embodiments

Now, the first embodiment of the present invention for accomplishing the first object will be described with reference to Figs. 1 - 7. Fig. 1 is a view showing the arrangement of cameras for constructing stereopsis. While the present embodiment will be explained as to an example in which the cameras are arranged in the horizontal direction, they may well be arranged in the vertical direction or in oblique directions.

In the present embodiment to be stated below, there will be referred to a method wherein one point to be

noted is set within the image of one eye and wherein

a corresponding point is detected from the image of

the other eye.

First, as shown in Fig. 2, small regions of certain

5 size are set around the point of note and in a direction

coupling the centers of the right and left images, and

the mean brightness of each small region is obtained.

Now, letting $\underline{n}$ denote the number of the small regions,

and I_i denote the mean brightness of the i-th small

10 region, a flow as indicated by Eq. (1) is evaluated:

$$A_i = I_i - \sum_{j=i-2}^{i+2} I_j \quad (i = 3, 4, \ldots, n - 2)$$

...(1)

Results obtained by such procedure for certain images

of the right eye and the left eye are shown in Figs. 3(a)

and 3(b). Here, an arrow indicates the small region

15 which includes the point of note.

A network, in which the magnitudes of the right

eye evaluated from Eq. (1) are denoted by R_i (i = 3, 4,

..., n — 2) and the magnitudes of the left eye by L_i

(i = 3, 4, ..., n — 2) and in which they are outflow

20 and inflow magnitudes, is organized as shown in Fig. 4.

The cost of transportation   per proper unit flow is

set for each branch of the network, and the flow which

permits transport at the minimum expense is found. Letting
X_{i-1}, X_i and X_{i+1} denote flows from the i-th nodal point
of right eye's image to the (i - 1)-, i- and (i + 1)-th
nodal points of left eye's image, respectively, the
position of the left eye corresponding to the i-th nodal
point of right eye's image is found as:

$$i + (X_{i+1} - X_{i-1})/R_i \qquad \qquad ...(2)$$

Results with the corresponding points obtained from
the transport volumes of the minimum expenses for the
example of Figs. 3(a) and 3(b) are shown in Fig. 5.

The left eye image is moved so that the corresponding
points of the nodal points including the point of note
may be superposed, and small regions which are still
smaller than the aforementioned small regions are set,
whereupon the corresponding points are found. The brightnesses
of the respective smaller regions are shown in Figs. 6(a)
and 6(b), while the calculated results of the corresponding
points are shown in Fig. 7.

This procedure is repeated whilst reducing the
size of the smaller region gradually, whereby the corresponding
point of left eye's image to the noted point of right
eye's image can be found.

Although, in the embodiment, the magnitudes of
outflow or inflow to each nodal point has been evaluated
with Eq. (1), the mean brightness I_i of the i-th small

region can also be directly used as the outflow or inflow

magnitude. Besides, the rate of change in brightness

as given by:

$$A_i = I_i - I_{i-1} \qquad \ldots(3)$$

5   can be used as the outflow or inflow magnitude.

Although, in the embodiment, the arrangement of

the branches of the network and the cost per unit flow

through each branch have been fixed, it is also possible

to lessen misrecognition in such a way that calculations

10   are repeatedly performed whilst altering the arrangement

of the branches or/and the cost per unit flow. That

is, calculations are repeated while the number of branches

is being increased in a direction toward the corresponding

point of the left eye from each nodal point of the right

15   eye found from the result of one time of calculation

or while the cost per unit flow in the direction is

being decreased, whereby misrecognition can be lessened.

Next, the second embodiment of the present invention

will be described with reference to Figs. 8(a) - 11(b).

20   Figs. 8(a) and 8(b) show some of mean brightnesses evaluated

every 4 x 4 small regions for successively obtained

images. Figs. 9(a) and 9(b) show results obtained by

subjecting the respective brightness values of Figs. 8(a)

and 8(b) to the second-order differentiation indicated

25   in Eq. (4):

$$A'(i, j) = 4 * A(i, j) - A(i + 1, j) - A(i - 1, j)$$
$$- A(i, j + 1) - A(i, j - 1)) \quad \ldots(4)$$

$A(i, j)$: mean brightness of 4 x 4 regions.

$A'(i, j)$: second-order differential value of $A(i, j)$.

In order to detect the corresponding points between Figs. 9(a) and 9(b), transport paths as shown in Fig. 10 are constructed. That is, transport paths are set from the (i, j)-th pixel 102 of the image 101 obtained at a time t to the (i', j')-th $(i' = i - 1, \underline{i}, i + 1$ and $j' = j - 1, \underline{j}, j + 1)$ pixels of the image 103 obtained at a time $(t + 1)$. Letting $A'(i, j)$ denote the second-order differential value of the (i, j)-th pixel 102 of the image 101 at the time $\underline{t}$, and $B'(i, j)$ denote the second-order differential value of the (i', j')-th pixel 104 of the image 103 at the time $(t + 1)$, the magnitudes of inflow from the respective pixels to the transport paths are set as follows:

(i, j)-th pixel at time $\underline{t}$: $A'(i, j)$,

(i', j')-th pixel at time $(t + 1)$: $-B'(i, j)$.

More specifically, in the pixel (i, j) at the time $\underline{t}$, $A'(i, j) > 0$ indicates the magnitude of inflow, and $A'(i, j) < 0$ the magnitude of outflow. Conversely, in the pixel (i', j') at a time $(t - 1)$, $B'(i', j') > 0$ indicates the magnitude of outflow, and $B'(i', j') < 0$ the magnitude of inflow.

Under the above conditions, the following minimum cost flow problem is considered:

Under conditions:

$$\sum_{(i', j') \in N_{t-1}} X(i, j)(i', j')$$

$$= \begin{cases} A'(i, j) - D(i, j) & ((i, j) \in E_t), \\ A'(i, j) & ((i, j) \notin E_t), \end{cases} \quad \ldots(5)$$

$$\sum_{(i, j) \in N_t} X(i, j)(i', j')$$

$$= \begin{cases} B'(i, j) - D(i, j) & ((i, j) \in E_{t-1}), \\ -B'(i, j) & ((i, j) \notin E_{t-1}), \end{cases} \quad \ldots(6)$$

minimize

$$Z = \sum_{(i, j) \in N_t} \sum_{(i', j') \in N_{t-1}} (i, j)i', j') \left| X(i, j)(i', j') \right| \quad \ldots(7)$$

Here, $X(i, j)(i', j')$ denotes the flow from the pixel (i, j) to the pixel (i', j') (provided that a minus flow can exist). N_t and N_{t-1} denote the sets of the pixels at the time t and the time $(t - 1)$ respectively, E_t and E_{t-1} the sets of pixels located at end parts of the images among the pixels at the time t and the time $(t - 1)$ respectively, and $C(i, j)(i', j')$ a cost factor for $X(i, j)(i', j')$. In addition, $D(i, j)$ and $D(i', j')$

denote dummy flows for the pixels located at the end parts of the images. The reason why such dummy flows are introduced, is that the differences between the images at the times $\underline{t}$ and $(t-1)$ attributed to the

5 movement of the object need to be canceled.

$C(i, j)(i', j')$ is set as follows:

$$C(i, j)(i', j') = \sqrt{(i, i')^2 + (j, j')^2} \qquad ...(8)$$

That is, the flows between the pixels located at the same positions in the images of the times $\underline{t}$ and

10 $(t-1)$ are set to be small.

From the solution of the minimum cost flow problem, the corresponding point (p_i', p_j') within thë image of the time $(t-1)$ to the pixel (i, j) is given by:

$$P_i' = i + \sum_{(i', j') \in N_{t-1}} \left| X(i, j)(i', j') \right| \times (i' - i)/T$$

15 $$P_j' = j + \sum_{(i', j') \in N_{t-1}} \left| X(i, j)(i', j') \right| \times (j' - j)/T$$

$$...(9)$$

Here, T is expressed as:

$$T = \sum_{(i', j') \in N_{t-1}} \left| X(i, j)(i', j') \right|$$

Fig. 11(a) shows parts corresponding to Fig. 10

as extracted from results obtained in this way. The

directions of arrows indicate the directions in which

the images of the respective pixels have moved, and

the lengths thereof indicate the magnitudes of the movements.

5   Regarding the movement magnitude, a length indicated

in Fig. 11(b) corresponds to a movement for two pixels.

It is also possible to enhance the detection accuracy

of corresponding points by repeating the procedure in

which the corresponding points thus found are replaced

10 with (i', j'), the cost factors for the respective transport

paths are altered in accordance with Eq. (8) and the

minimum cost flow problem of Eqs. (5) – (7) is solved.

Although, in the present embodiment, the second-

order differential value of the brightness in each pixel

15 has been used as the quantity flowing through the transport

path, it is also allowed to utilize the brightness of

each pixel, a value obtained through a Laplacian filter,

a deviation from a brightness obtained as a floating

average, or the like.

20 Besides, to the end of enhancing the detection

accuracy of corresponding points, it is also possible

to divide each image into small regions, to subject

the mean brightnesses thereof to the processing stated

before, and to reduce the size of the small regions

25 gradually. The procedure of gradually reducing the

size of the small regions may well be differentiation
or gradual reduction in the size of the Laplacian filter
in the case of using the filter.

Fig. 12 is a block diagram of the whole system

5 of an apparatus for determining a pair of corresponding
points between images in accordance with the present
invention. Every two image data for determining the
corresponding points are stored in image memories 121.
The data of the image memories 121 are subjected to mean value

1o calculations or to pre-processing with differentiation
filters, whereupon they are sent to a node current memory
122 as the magnitudes of outflow and inflow at the nodal
points of a transport network. Using the data of a
current cost memory 123, which stores the current costs

15 of the respective branches of the transport network,
and the data of the node current memory 122, the minimum
cost flow calculation is performed in a processor 125,
and the resulting currents of the respective branches
are stored in a current memory 124. Calculations for

2o determining the corresponding points are performed in
the processor 125 by the use of the data of the current
memory 124, and the result is stored in a pair of correspond-
ing points-memory 126.

In case of precisely determining the corresponding

25 points, the calculations for determining the corresponding

points are performed in the processor 125 by the use of the data of the current memory 124, the result is used for altering the data of the current cost memory 123, and the minimum cost flow calculation is performed

5   by the processor 125 again.

After repeating this procedure several times, the calculations for determining the corresponding points are performed using the data of the current memory 124. Then, the precise determination of the corresponding

10   points is possible.

As set forth above, according to the present invention, in determining corresponding points in a pair of stereo images, the brightnesses of the respective parts of the images or/and the rates of change in brightness

15   thereof can also be considered. This achieves the effect that misrecognition can be lessened.

In addition, the detection of corresponding points between successive images can be converted into a problem for finding the minimum cost flow in a network. This

20   achieves the effect that the corresponding points can be readily detected by repeating simple calculations.

Next, the third embodiment of the present invention for accomplishing the second object will be described with reference to Figs. 13 - 21.

25   Fig. 13 is a block diagram of the whole system

of a three-dimensional distance measuring apparatus
to which the present invention is applied. Information
expressive of an image picked up by a TV camera.131
is once stored in an image memory 132. In case of stereopsis,
5   two images simultaneously picked up from different positions
are stored. However, in the presence of the relative
movement between a measuring instrument and an object
to be measured, two images picked up at different times
may well be stored. In this example, a processor 130
10 is composed of a pre-processor 133, a pair of corresponding
points-determining means 134 and a distance calculator
135. The pre-processor 133 reads out the image information
from the image memory 132, calculates the mean brightnesses
of respective small regions of proper size, the rates
15 of change in brightness relative to the adjacent regions,
or the like, and sends the results to the corresponding
points-determining means 134. The corresponding points-
determining means 134 evaluates the corresponding relation
between the small regions by the use of the received
20 data and gives the pre-processor 133 instructions on
the basis of the result. In accordance with the instructions,
the pre-processor 133 performs the alteration of the
regions, the shift of the image data, etc. and thereafter
executes the above-stated pre-processing again. When
25 such processing has been repeated a suitable number

of times and the calculated result of the corresponding

relation has sufficiently converged, this calculated

result is sent to the three-dimensional distance calculator

135, in which a position is calculated.

5   Hereinbelow, the details of the processes in the

respective portions will be explained by taking the

case of stereopsis as an example. In the case of stereopsis,

two TV cameras 131 corresponding to the right and left

eyes are disposed, and their positions are known. In this case,

1o   search for corresponding points can be localized or limited on-

epipolar lines. As shown in Fig. 14, the "epipolar

lines" are the lines of intersection 141 between a plane,

which is determined by the three points of the lens

center 142 of the right camera, the lens center 143

15   of the left camera and an object point P, and the images

144 and 145 of the respective cameras (refer to 'Jōhō-Shori

(Information Processing)', Vol. 24, No. 12, p. 1449,

"Study on Image Understanding in U. S. A."). The image

memory 132 stores the image information as converted

2o   so that the epipolar lines may agree with the corresponding

scanning lines of both the images. Owing to the storage

in such form, it suffices to examine the corresponding

relation between points on the corresponding scanning

lines of both the images.

25   Next, the process in the pre-processor 133 will

be elucidated. Referring to Fig. 15, scanning lines

153 to be handled for the determination of corresponding

points in left eye's image 151 and right eye's image

152 agree with epipolar lines. The pre-processor 133

5   takes up small regions 154_i (i = 1, 2, ..., m) of S x S

pixels including the scanning lines 153 centrally, and

calculates the mean brightnesses of the small regions

in accordance with the following equations:

$$AR(i) = \left\{ \sum_{y=\ell-\frac{s}{2}+1}^{\ell+\frac{s}{2}} \sum_{x=(i-1)s}^{i_s-1} RI(x, y) \right\} / s^2$$

10

$$\qquad \qquad \qquad \qquad \qquad \qquad \qquad ...(10)$$

$$AL(i) = \left\{ \sum_{y=\ell-\frac{s}{2}+1}^{\ell+\frac{s}{2}} \sum_{x=(i-1)s}^{i_s-1} LI(x, y) \right\} / s^2$$

$$i = 1, 2, ..., m$$

Here, s denotes the number of pixels of one side of

the small region, RI(x, y) and LI(x, y) denote the magnitudes

of brightness possessed by the pixels of right eye's

15   image and left eye's image at a position (x, y) respectively,

ℓ denotes No. of the scanning line to determine the

corresponding point and to evaluate a three-dimensional

distance, and m denotes the number of the small regions.

Subsequently, using the brightnesses of the respective

20   small regions thus obtained, the rates of change in

brightness (differential values) are calculated in accordance
with the following equations:

$$\left. \begin{array}{l} BR(i) = AR(i + 1) - AR(i) \\ BL(i) = AL(i + 1) - AL(i) \end{array} \right\} \quad \ldots (11)$$

$$i = 1, 2, \ldots, m - 1$$

5

The above is the content of the process in the
pre-processor 133. Next, the corresponding points-
determining means 134 will be elucidated. In the corresponding
points-determining means 134, a transport network as

10 shown in Fig. 16(a) is supposed, and flows through the
individual transport paths thereof are calculated. The
network in Fig. 16(a) is constructed in such a way that
the transport paths 165 having resistance values R_{ij} are
laid between constant current sources 161 as inflow

15 sources which have current values corresponding to the
respective differential values BR(i) (i = 1, 2, ...,
m — 1) for the right eye image and constant current sources
162 as outflow sources which have current values corresponding
to the respective differential values BL(j) (j = 1, 2,

2o ..., m — 1) for the left eye image. The connectional
destinations of the transport paths 165 to fan out from
each nodal point i can be actually limited to a suitable
number (for example, 9 or 11) including the opposing
nodal point and neighboring ones, and only three destinations

are exemplified in Fig. 16(a). In this regard, however,

nodal points 163 and 164 at i = 0, m and j = 0, m are

provided in order to compensate for uniqueness owned

by the end parts of the images. More specifically, at

5   the end parts of the right eye and left eye images, there

are object points which exist in one image but which do

not exist in the other image. Since the corresponding

point of such object point does not exist in the opposite

image, such points are caused to correspond to the aforemen-

10   tioned nodal points 163 and 164.

Conditional equations to be satisfied by the transport

network thus constructed are as follows:

$$
\left.
\begin{aligned}
BR(i) &= \sum_j x_{ij} \quad (i = 1, \ldots, m-1) \\
BL(j) &= \sum_i x_{ij} \quad (j = 1, \ldots, m-1) \\
V_i - V_j &= R_{ij} \cdot x_{ij} \quad (i = 0, \ldots, m; \; j = 0, \ldots, m)
\end{aligned}
\right\} \cdots (12)
$$

15   where V_i (i = 0, m) = 0 and V_j (j = 0, m) = 0

hold. Here, V_i and V_j denote the potentials of a nodal point

166   (i = 0, ..., m) for right eye's image and a nodal

point 167 (j = 0, ..., m) for left eye's image respectively,

20   and x_{ij} denotes the value of current flowing from the

nodal point i to the nodal point j.

In the corresponding points-determining means 134,

a series of calculations to be mentioned below are executed

for the transport network several times, and the corresponding

points are determined when a steady solution has been

substantially reached.

(I) Set the initial potentials of the respective nodal

5   points ($i = 1, ..., m - 1$; $j = 1, ..., m - 1$) and the

initial values of the resistances R_{ij} of the respective

transport paths.

(II) Evaluate the current values x_{ij} ($i = 0, ..., m$;

$j = 0, ..., m$) of the respective branches in accordance

10 with:

$$x_{ij} = (V_i - V_j)/R_{ij} \qquad \qquad ...(13)$$

(III) Update the potentials of the respective nodal

points in accordance with:

$$\left. \begin{array}{l} V_i' = V_i + \mathcal{E}\left\{BR(i) - \displaystyle\sum_j x_{ij}\right\} \\[1em] \hspace{4cm} i = 1, ..., m - 1 \\[1em] V_j' = V_j - \mathcal{E}\left\{BL(j) - \displaystyle\sum_i x_{ij}\right\} \\[1em] \hspace{4cm} j = 1, ..., m - 1 \end{array} \right\} \quad ...(14)$$

Here, $\mathcal{E}$ denotes a correction factor.

(IV) Select a proper threshold value α, and update the

20 resistance values of the respective transport paths in

accordance with the following rules:

$$\left. \begin{array}{ll} |x_{ij}| < & : \text{Do not update.} \\[1em] |x_{ij}| \geq & : \text{Update with the following equation.} \end{array} \right\} ...(15)$$

$$R'_{k\ell} = R_{k\ell} - w(\overline{i-j} - \overline{k-\ell}) \cdot |x_{ij}| / \beta$$

$$\left(\begin{array}{l} k = i - 1, \ i, \ i + 1 \\ \ell = k - i + j - 3, \ k - i + j - 2, \ \ldots, \ k - i + j + 3 \end{array} \right)$$

Here, $w(\overline{i-j} - \overline{k-\ell})$ denotes weighting factors as
indicated in Fig. 16(b), and β denotes a correction
factor. After the updating process, the step (II) is
returned to.

Putting

$$d = \sum_j (i - j) \ |x_{ij}| / \sum_j |x_{ij}|$$

when the steady solution has been obtained in the above
way, the i-th small region corresponds to the (i + d)-th
small region. By the way, when $\underline{d}$ contains a decimal
part, this decimal part is interpreted as indicating
a point between one small region and the next small
region. When the processing for the small regions of
certain size (for example, s = 8) has ended, the result
is utilized to perform similar calculations for still
smaller regions (for example, s = 4), whereby the corresponding
relation in pixel unit can be finally determined.

The above are the processing steps in the corresponding
points-determining means 134. Herein, the step (IV)
has the following significance. In general, in the
environment in which a moving object moves, the surface
of the object is considered to smoothly change in most

places (this is termed the "continuity assumption"),
and a change in distance is small between the adjacent
pixels. Besides, in determining the corresponding points,
the correspondence is successively carried out from
5   points of larger differential values, whereby erroneous
correspondence can be avoided. More specifically, as
indicated by the rules of the step (IV), if there is
the transport path of greater flow, the flow between
the nodal points $\underline{i}$ and $\underline{j}$ at both the ends of this transport
10 path is increased, while between the nodal points neighboring
those $\underline{i}$ and $\underline{j}$ ($j \pm 1,\; j \pm 2,\; j \pm 3$), the resistance
values are updated by the weighting $\underline{w}$ which decreases
the flow as the point $\underline{j}$ becomes remoter. Further, as
regards the transport paths extended from the nodal
15 points neighboring that $\underline{i}$, the resistance values are
updated by   the same weighting as stated before (that is,
the weighting which maximizes the resistance values
at $j \pm 1$). Thus, the continuity assumption is satisfied.

Referring now to Fig. 17, the distance calculator
20 135 will be elucidated. As illustrated in Fig. 17, V_L
and V_R denote the central coordinates of the optical
systems of the respective left and right cameras, P_L
(x_L, y_L) and P_R (x_R, y_R) denote the positions of images
which one point $P(x, y, z)$ on the surface of an object
25 ahead forms on the imaging screens of the left and right

cameras, and $\underline{f}$ denotes the focal length of a lens. At
this time, the position of the point P is given by the
following as is well known:

$$
\begin{cases}
x = \dfrac{x_L \, V_R - x_R \, V_L}{x_L - x_R} \\[2mm]
y = f \, \dfrac{- V_L + V_R}{x_L - x_R} \\[2mm]
z = \dfrac{y_L \, (- V_L + V_R)}{x_L - x_R}
\end{cases}
\qquad \ldots (16)
$$

In the distance calculator 135, the three-dimensional
distances of the respective points on the object corresponding
to the points on the images are calculated using Eqs. (16)
and the values (x_R, y_R) and (x_L, y_L) of the respective
points which are the calculated results of the corresponding
points-determining means 134.

Examples of the processed results according to
the present embodiment are illustrated in Figs. 18(a)
and 18(b) – Figs. 20(a) and 20(b). Figs. 18(a) and
18(b) show right eye's image and left eye's image on
a certain pair of corresponding scanning lines as stored
in the image memory 132, respectively, and the axis
of abscissas represents pixel No., while the axis of
ordinates the brightness. As to the image data, the
mean brightnesses of every small regions of 8 x 8 pixels

and the differential values thereof are calculated in
the pre-processor 133, and the calculations for determining
the corresponding points are executed in the corresponding
points-determining means 134. Subsequently, the initial
5   values of the resistances are determined using these
results, and the series of calculations employing the
mean brightnesses of every small regions of 4 x 4 pixels
are executed. Thenceforth, the precision is gradually
enhanced in similar fashion. Figs. 19(a) and 19(b)
10 show differential values for brightnesses obtained every
pixel (the data of Figs. 18(a) and 18(b) stored in the
image memory 132), with the former corresponding to
the right eye image and the latter to the left eye image.
Results finally obtained in the corresponding points-
15 determining means 134 are shown in Fig. 20(a). The
axis of abscissas represents pixel No., while the axis
of ordinates represents the number of pixels by which
left eye's image deviates rightwards relative to right
eye's image. Here, regarding only points whose differential
20 values have absolute values of at least 20.0, the calculated
results are indicated as they are, whereas the other
points are interpolated between the aforementioned points.
Fig. 20(b) shows the y-directional distances (depths)
of results calculated on the basis of Fig. 20(a) by
25 the three-dimensional distance calculator 135.

Thus far, the embodiments for a pair of stereo
images have been stated. The present invention is not
restricted to the case where corresponding points may
be found on only the corresponding scanning lines as
5   in the pair of stereo images, but it is also applicable
to a case where corresponding points need to be found
within a two-dimensional extent as in images obtained
in such a way that an object relatively displaced in any
desired direction is imaged at different times.

10   Fig. 21 shows a modification of the network for
determining unidimensional corresponding points as depicted
in Fig. 16(a), the modification being capable of determining
corresponding points in two dimensions. Constituents
corresponding to those of Fig. 16(a) are indicated by
15   the same symbols. The network of Fig. 21 is repeatedly
subjected to processes similar to those in the case
of stereopsis, whereby the corresponding points can
be determined between the images. A method for evaluating
a distance to an object point on the basis of the corresponding
20   points between the images may well be a method described
in Japanese Patent Application No. 58-194251.

According to the present invention, in determining
a pair of corresponding points, the density information items
of images can be handled as they are (without quantizing
25   them into binary values), and not only the correspondence

between pixels, but also the correspondence of a pixel

in one image to the position between pixels in the other

image is possible. Accordingly, precise correspondence

becomes possible, and in turn, the measuring accuracy

5   of a position or a distance is enhanced.

PS/bi

<u>Claims:</u>

1. A method for determing
corresponding points in images characterized by constructing
a transport network which is composed of transport paths
for transporting quantities of light of respective pixels

5   from one image to the other image, and finding corresponding
pixels on the basis of a transport state between pixels
which permit the transport at a minimum cost.

2. A method for determining corresponding points
in images according to Claim 1, wherein said transport

10   network is constructed with its transport magnitudes
being magnitudes which are obtained by subjecting the
two images to differential calculations, and the corresponding
pixels are found on the basis of the transport state
between the pixels which permit the transport at the

15   minimum cost.

3. A method for determining corresponding points
in images according to Claim 1, wherein said transport
network is constructed with its transport magnitudes
being deviations from floating average values of the

20   two images, and the corresponding pixels are found on
the basis of the transport state between the pixels
which permit the transport at the minimum cost.

4. A method for determining corresponding points

in images according to Claim 1, wherein each of the
two images is divided into a plurality of partial images,
mean quantities of light of the respective divided partial
images are subjected to processing in which the corresponding
5   pixels are found on the basis of the transport state
between the pixels permitting the transport at the minimum
cost, and a size of said each partial image is gradually
reduced, thereby to find the corresponding pixels.

        5.   A method for determining corresponding points
10 in images according to Claim 1, wherein said transport
state is a value of the transport magnitude in a case
where the two images are a pair of stereo images obtained
by two imaging means arranged at a short distance.

        6.   A method for determining corresponding points
15 in images according to Claim 1, wherein said transport
state is a distribution of values of the transport magnitudes
in a case where the two images are successive images
changing in succession.

        7.   A method for determining corresponding points
20 in images according to Claim 2, wherein a size of a
filter for use in the differential calculation is reduced
stepwise, and processing in which the corresponding
pixels are found on the basis of the transport state
between the pixels permitting the transport at the minimum
25 cost is repeated, thereby to detect the corresponding points.

8.   A method for determininα
corresponding points in images characterized by constructing
a transport network model so that flows at inflow points
corresponding_to various points of one image and at

5   outflow points corresponding to various points of the
other image may become magnitudes of a feature quantity
of corresponding points on the images, and determining
the pair of corresponding points composed of the inflow
point and the outflow point on the basis of a flow distribution

1o   within the constructed network.

9.   A method for determining corresponding points
in images according to Claim 8, wherein said transport
network model is an electric circuit in which the flows
correspond to current values, and transport paths between

15   the respective points correspond to resistances.

10. A method for determining corresponding points
in images according to Claim 8, wherein the feature
quantity of each point of the image is a rate of change
in brightness relative to the adjoining points.

FIG. 1

FIG. 2

FIG. 3a

FIG. 3b

FIG. 4

R_3 R_4 R_5 R_{i-1} R_i R_{i+1} 31 R_{n-2}

33

32

L_3 L_4 L_5 L_{i-1} L_i L_{i+1} L_{n-2}

FIG. 5

41

42

FIG. 6a

50
-50

50

FIG. 6b

50
-50

50
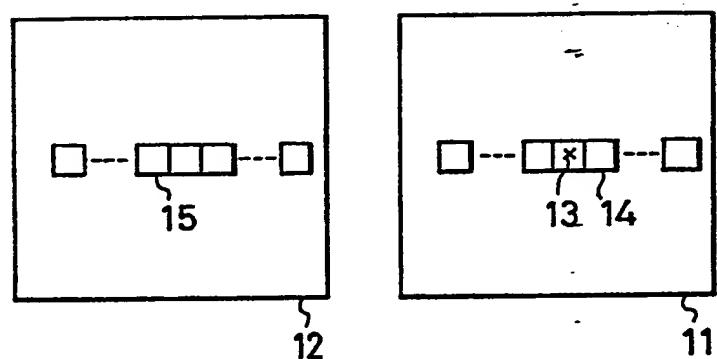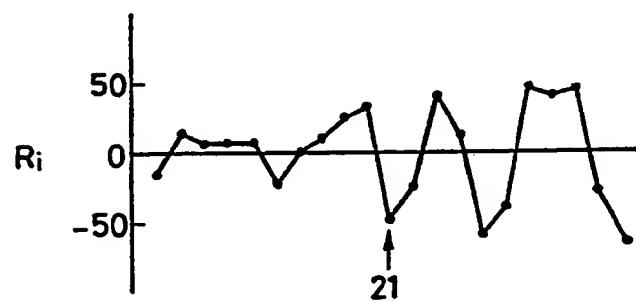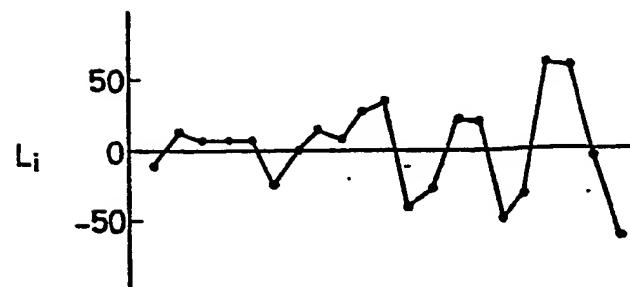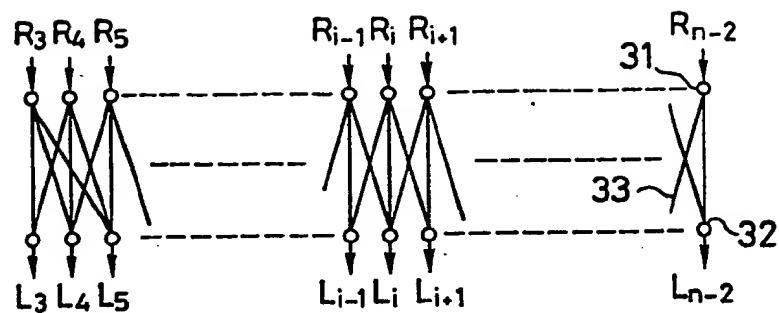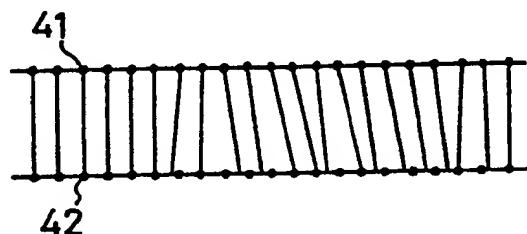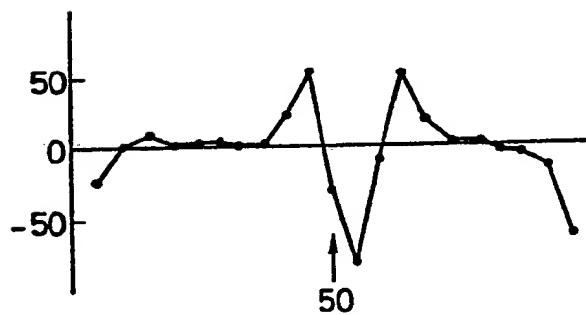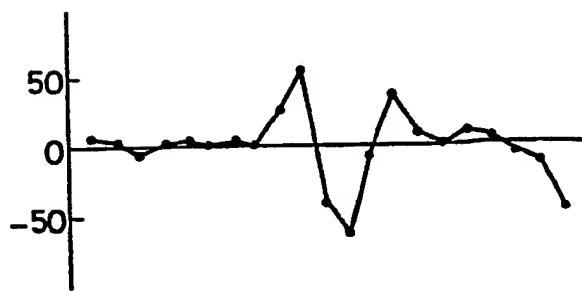
FIG. 7
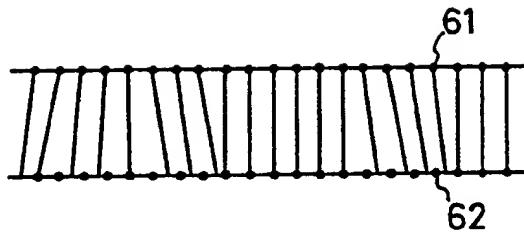
FIG. 8a

```
68.6    55.8    47.4    40.6    38.5    34.1    29.7    28.5    27.2    27.0
114.1   99.8    88.5    80.0    68.1    57.4    51.8    47.4    46.9    43.8
133.1   121.6   110.8   101.4   92.1    77.0    68.8    63.8    63.2    58.9
175.8   195.6   188.7   180.6   169.7   129.4   76.1    72.6    69.8    64.5
207.6   228.1   218.6   208.7   195.6   127.6   80.2    75.4    71.8    66.0
119.6   124.9   119.0   111.6   103.2   77.5    57.8    60.2    60.5    53.2
49.3    52.8    49.3    48.2    42.8    33.0    24.6    20.0    22.4    20.9
20.8    25.6    24.0    20.9    21.1    17.9    15.4    5.7     7.1     12.9
22.1    19.3    20.3    17.4    18.9    17.6    14.1    10.7    9.0     13.3
35.4    32.4    22.5    9.3     3.9     3.3     2.2     2.3     1.7     2.6
```

FIG. 8b

```
82.3    73.1    66.3    60.9    55.4    49.9    42.6    40.4    38.3    38.3
94.5    88.1    88.8    77.6    74.0    67.3    57.6    52.8    50.0    47.8
122.6   130.4   164.3   162.5   157.5   149.4   121.8   60.4    52.9    50.6
122.4   158.3   190.7   186.3   179.1   170.6   124.1   38.8    54.9    52.3
70.9    89.2    98.7    95.6    91.9    82.6    63.6    42.9    38.9    42.8
33.3    38.3    39.2    40.4    37.6    35.1    24.4    19.1    12.8    12.4
15.7    17.3    13.9    15.5    15.1    16.3    13.2    12.1    7.8     1.1
15.6    12.9    13.8    14.3    16.1    13.8    13.8    12.4    10.8    8.9
27.1    30.3    31.1    29.3    10.1    3.4     4.1     0.4     1.5     0.7
17.8    24.6    27.1    22.6    8.2     0.4     0.2     0.0     0.0     0.0
```

FIG. 9a

```
  19.0   16.0   21.5    4.3   -1.2    3.8   -1.4    6.0
 -53.0  -56.9  -57.9  -47.9  -39.6    6.3    3.4   13.4
  68.4   49.2   53.8   81.1   67.1  -46.4    5.1    7.3
 165.6  129.8  128.4  173.3   27.8  -16.2   16.8   15.3
 -20.0  -28.3  -32.6  -14.8  -11.6  -11.3   27.1   34.4
 -37.8  -47.0  -31.8  -34.5  -30.8  -27.8  -32.9  -18.8
 -14.4  -20.0  -27.2  -16.0  -15.4   -0.6  -30.5  -21.5
 -23.1   -2.2    0.1   15.7   16.3   10.3   11.7    3.3
```

FIG. 9b

```
 -29.3  -61.1  -70.8  -61.8  -61.9  -54.2    2.7    8.3
 -11.6   89.8   64.3   64.9   80.6   95.8  -44.8   -4.1
 110.5  155.1  117.3  110.2  147.3   81.4  -47.1   16.9
  -9.5  -19.9  -34.8  -27.4  -31.0  -19.5   -8.6    2.1
 -25.7  -34.5  -26.4  -32.3  -20.3  -33.3  -15.9  -27.1
 -11.8  -30.3  -21.7  -24.9  -12.2  -13.8   -4.2   -5.7
 -25.3  -16.9  -17.5  -11.3    5.5   11.5   12.8   12.7
  25.6   23.7   39.3  -16.8  -14.8   -1.2  -16.6   -5.9
```
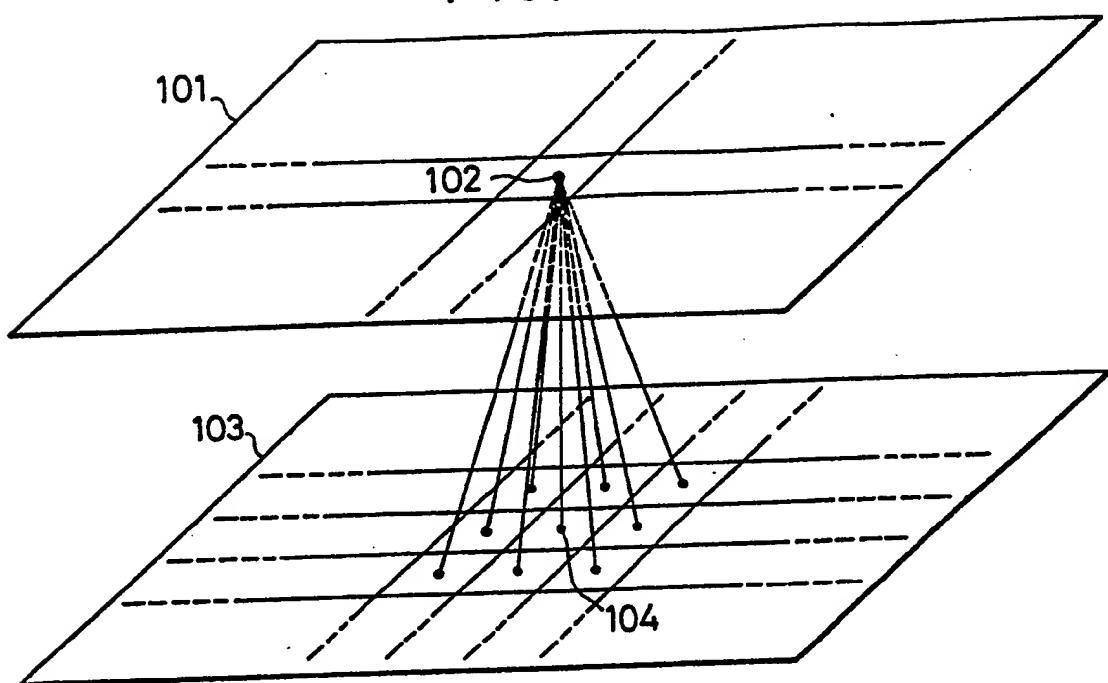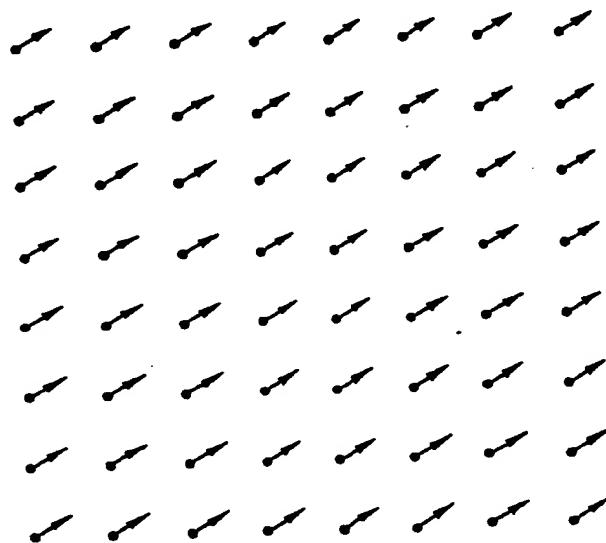
FIG. 10

FIG. 11a

FIG. 11b
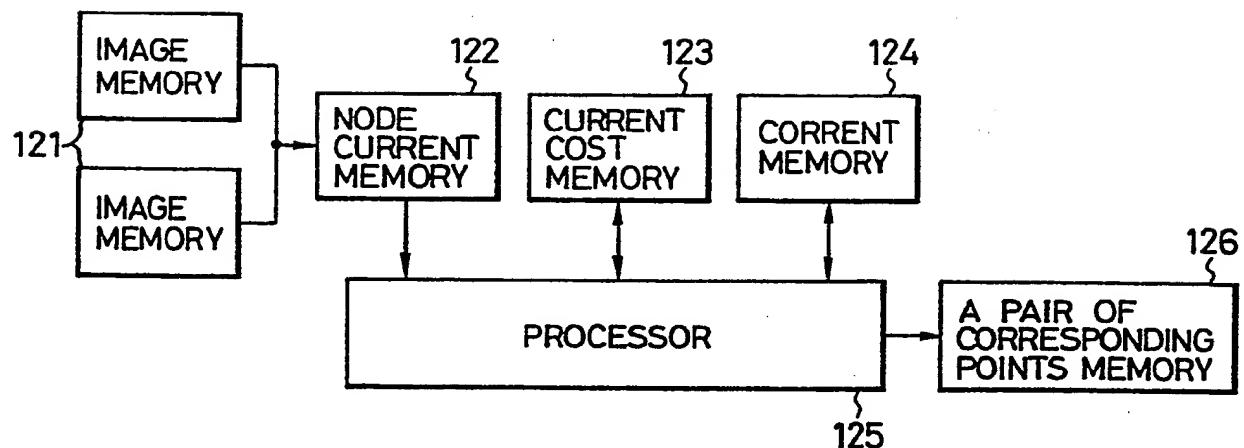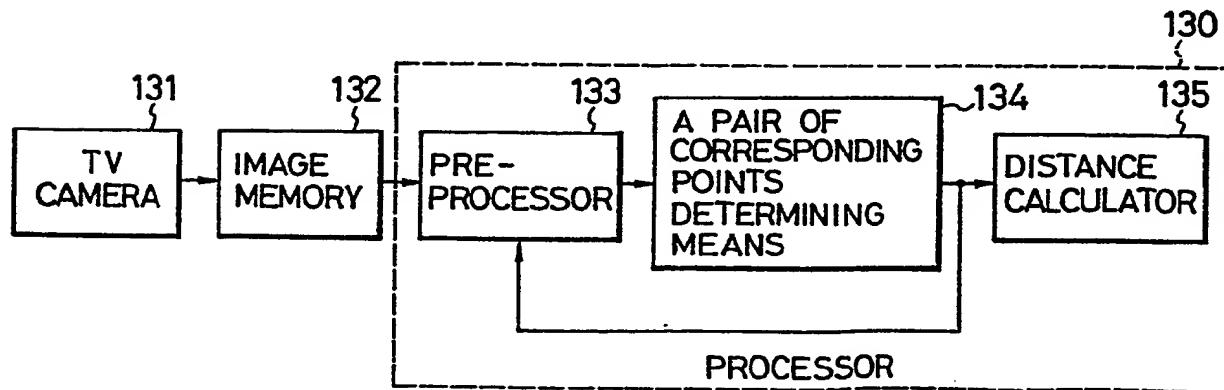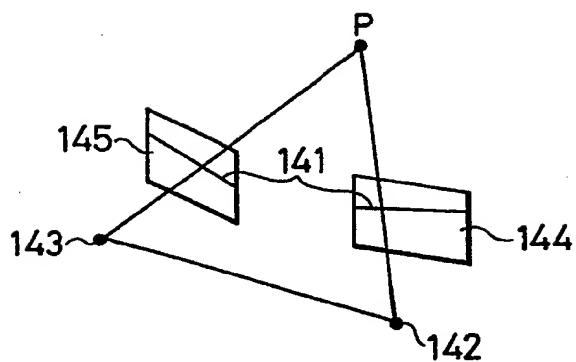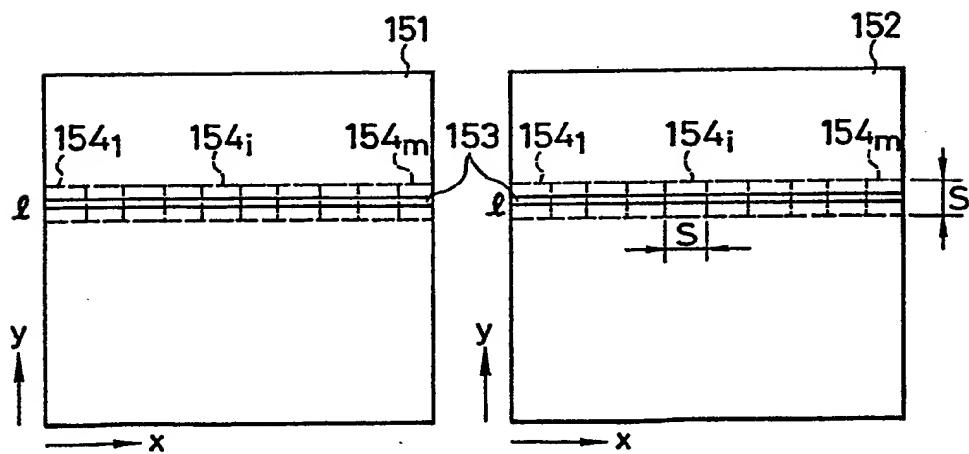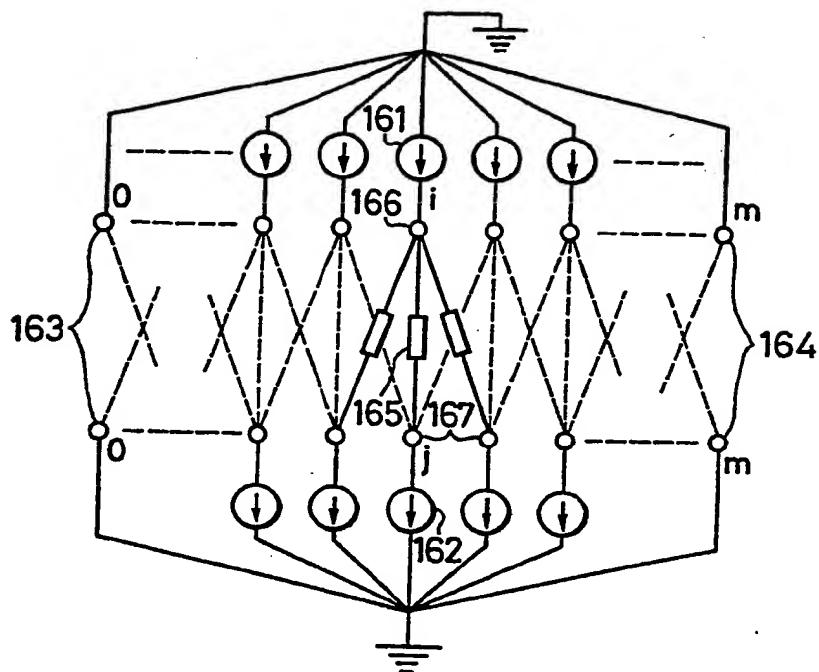
FIG. 12

```
┌──────────┐
│  IMAGE   │
│  MEMORY  │──┐        122          123          124
└──────────┘  │      ┌────────┐  ┌────────┐  ┌────────┐
121 ┤          ├──▶   │ NODE   │  │CURRENT │  │CORRENT │
    │          │      │CURRENT │  │ COST   │  │ MEMORY │
┌──────────┐  │      │MEMORY  │  │MEMORY  │  │        │
│  IMAGE   │  │      └────────┘  └────────┘  └────────┘
│  MEMORY  │──┘          │           ↕           ↕              126
└──────────┘             ↓                                   ┌────────────┐
                    ┌─────────────────────────────────┐      │ A PAIR  OF │
                    │          PROCESSOR              │──▶   │CORRESPONDING│
                    └─────────────────────────────────┘      │POINTS MEMORY│
                                   125                        └────────────┘
```

FIG. 13

```
                                                                    130
  131         132         133        ┌──────────────┐   134      135
┌──────┐   ┌────────┐   ┌────────┐   │  A PAIR  OF  │         ┌──────────┐
│  TV  │   │ IMAGE  │   │ PRE-   │   │ CORRESPONDING│         │ DISTANCE │
│CAMERA│──▶│ MEMORY │──▶│PROCESSOR│─▶│   POINTS     │────────▶│CALCULATOR│
└──────┘   └────────┘   └────────┘   │ DETERMINING  │         └──────────┘
                           │         │    MEANS     │
                           │         └──────────────┘
                           └──────────────┘
                              PROCESSOR
```

FIG. 14

P

145

141

143

144

142

FIG. 15

151

152

154_1　　154_i　　154_m　153　154_1　　154_i　　154_m　S

ℓ　　　　　　　　　　　　　　ℓ　　　　S

y　　　　　　　　　　　　　　y

x　　　　　　　　　　　　　　x

FIG. 16a

FIG. 16b

FIG. 17

FIG. 18a

BRIGHTNESS

200

100

0

32   64   96   128

PIXEL NUMBER

FIG. 18b

BRIGHTNESS

200

100

0

32   64   96   128

PIXEL NUMBER
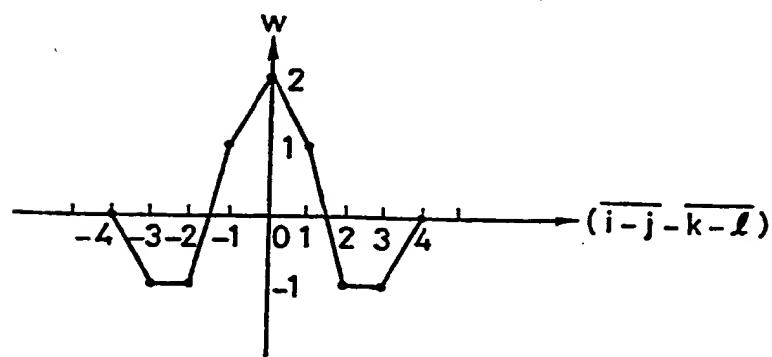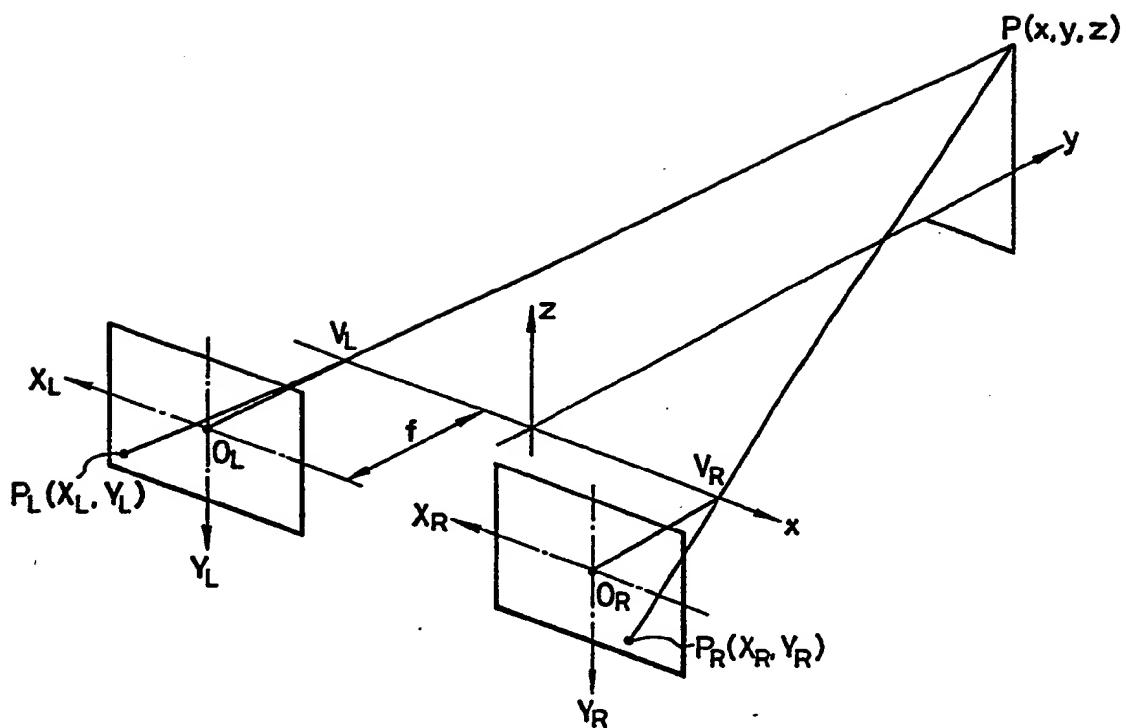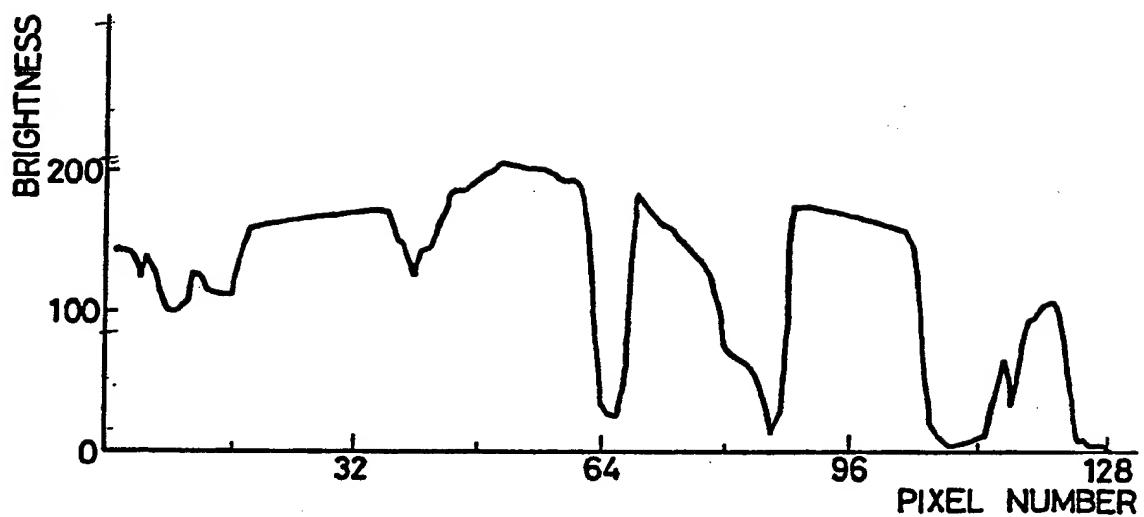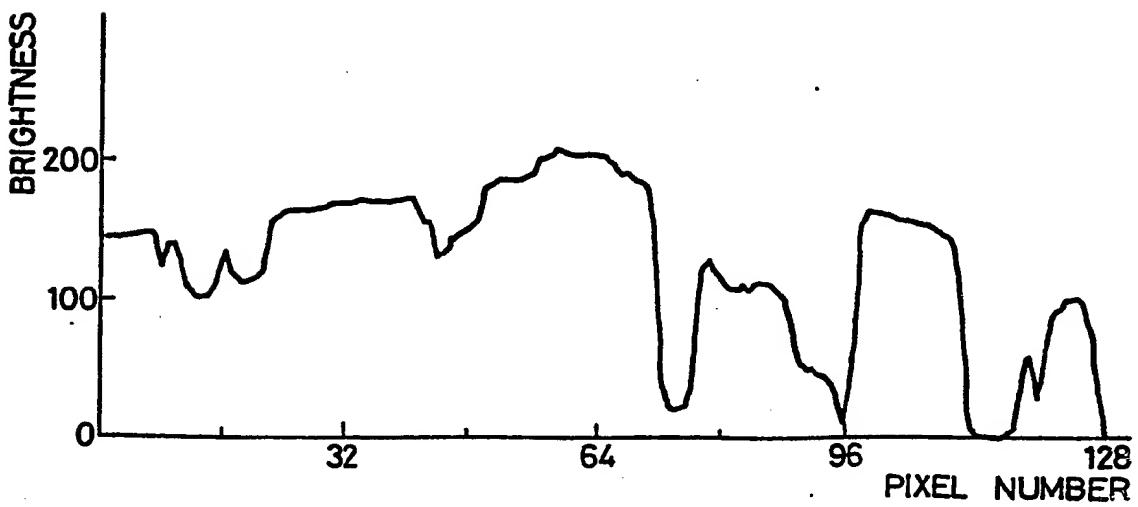
FIG. 19a

FIG. 19b
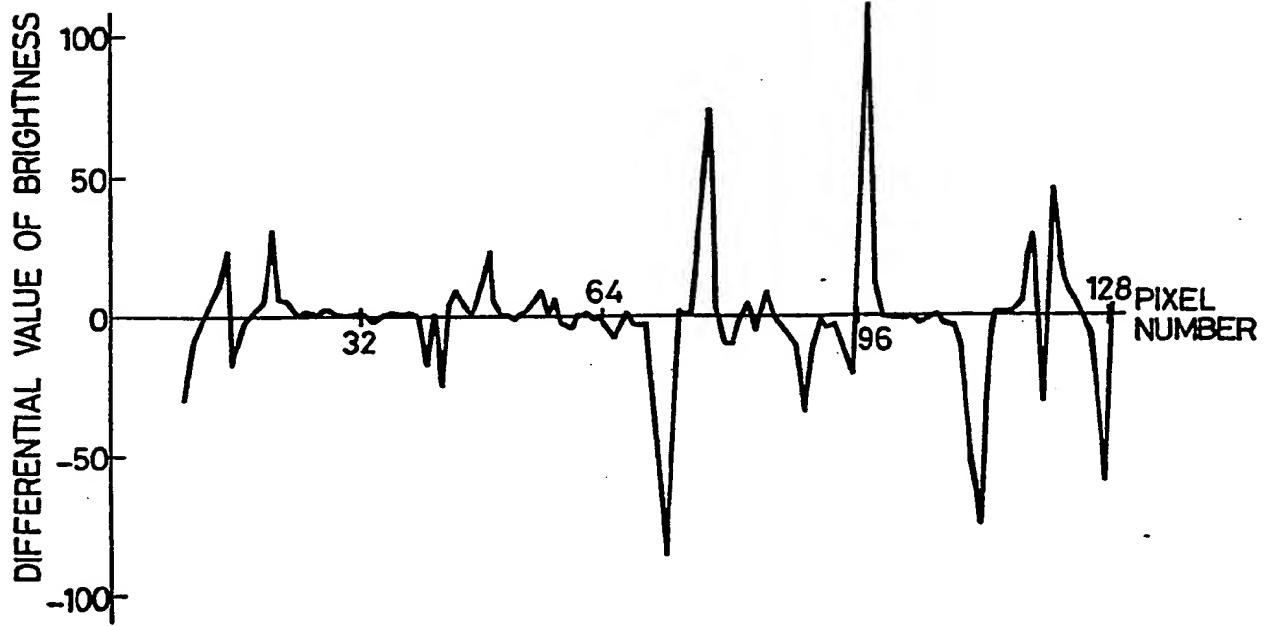
FIG. 20a

DEVIATION BETWEEN RIGHT EYE'S IMAGE AND LEFT EYE'S IMAGE

PIXEL NUMBER

FIG. 20b

y(m)

PIXEL NUMBER

0158984

FIG. 21

(12)   **EUROPEAN PATENT APPLICATION**

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(54) **Method for determining a pair of corresponding points between images.**

(57) A transport network is constructed of transport paths which transport quantities of light possessed by respective pixels (102,104) from one of two images (101,103) to the other, and a pair of corresponding points between the two images is found on the basis of the magnitude of light transport between the pixels minimizing the cost of transportation or a distribution of such magnitudes.

A transport network model is constructed so that flows at inflow points corresponding to various points on one image and at outflow points corresponding to various points on the other image may become magnitudes of a feature quantity of the respectively corresponding points on the images, and a pair of corresponding points composed of the inflow point and the outflow point is determined on the basis of a distribution of the flows within the network model.

FIG. 10

EP 0 158 984 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 85 10 4439

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
A	4E CONGRES DE RECONNAISSANCE DES FORMES ET INTELLIGENCE ARTIFICIELLE, Paris, 25th-27th January 1984, pages 481-491; M. FORTIN: "Recalage d'images multi-sources" * Pages 484,485 *	1,8	G 06 F 15/70
A	AU-A- 495 917 (CONTROL DATA CORP.) * Pages 3,13,17 *	1,8	
A	COMPUTER GRAPHICS AND IMAGE PROCESSING, vol. 17, no. 3, November 1981, pages 238-248, Academic Press, Inc., New York, US; K. PRAZDNY: "Determining the instantaneous direction of motion from optical flow generated by a curvilinearly moving observer" * Abstract; pages 239-246 *	1,8	

TECHNICAL FIELDS SEARCHED (Int. Cl.4)

G 06 F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	24-11-1988	CHATEAU J.P.

EPO FORM 1503 03.82 (P0401)